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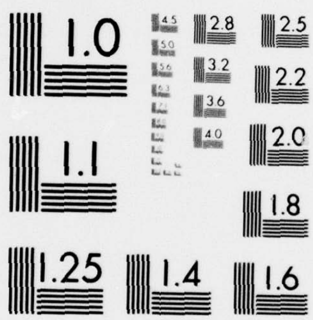

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CONTROL OF NONLINEAR SYSTEMS

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PRINCIPAL INVESTIGATOR: Allan E. Pearson

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Control Systems, Missile Intercept Guidance and Control, Feedback Stabilization, Time Varying Systems, Nonlinear Systems, System Identification, Signal Estimation.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results are summarized for the feedback stabilization of linear time varying differential and discrete-time linear systems, as well as a class of differential-delay systems. Extensions are described for a control law which tolerates a large class of nonlinearities in the loop without destroying stability. Research results are also described for the control of a class of intercept systems including its interpretation as a commutative bilinear system and a feedback control law which incorporates least → next page

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20. Abstract continued .

squares estimation of the target speed and turning rate. Results are described for parameter identification of a class of nonlinear systems with particular attention given to the identification of parameters for a helicopter system in longitudinal motion using input-output data on a finite time interval. Extensions to a signal estimation problem are indicated.

TABLE OF CONTENTS

I. INTRODUCTION

This progress report covers a seventeen month period preceding September 30, 1978, and is the third such progress report filed under grant AFOSR-75-2793. The personnel listed below received at least partial support from the grant during this period. Completed and continuing research is discussed in Section III.

II. SUPPORTED PERSONNEL

Y. K. Chin, Research Assistant

J. M. Mocenigo, Research Assistant

A. E. Pearson, Professor of Engineering

K. B. Yu, Research Assistant

III. RESEARCH COMPLETED AND CONTINUING RESEARCH

The published papers which have appeared during this period are listed chronologically in Section IV. References [2,3,4, and 7] are concerned with various aspects of feedback stabilization of linear systems in which the gain matrix in the feedback loop is related either directly or indirectly to the inverse of the controllability Gramian for the open loop system. References [3,4, and 7] are concerned with continuous differential and discrete time finite deimensional linear systems, both fixed and time varying. A significant feature of these results is that the gain matrix for the stabilizing control law can be obtained by the integration of a certain Riccati type ordinary differential equation over a finite time interval as opposed to the infinite time integration interval required for the standard steady state optimal regulator for time varying systems. Even in the case of time invariant systems the control law is easier to obtain than solving the algebraic matrix Riccati equation which attends the standard linear optimal regulator. Another interesting aspect to these results is that the pure integration of the gain matrix for this control law leads to another (new) control law which possesses a higher degree of tolerance to nonlinearities in the feedback loop without destroying stability than is permitted with other linear feedback optimal regulators. This latter research is still in progress and is so indicated under Section V. Reference [2] gives sufficient conditions for feedback stabilization of a class of continuous time linear differential-difference systems, i.e. systems containing a pure time delay, and utilizes a gain matrix in the feedback loop which is related to the control law of references [3,4, and 7].

References [1, 8 and 9] relate to various aspects in the control of a class of nonlinear continuous time systems which was motivated by a missile intercept control problem. In reference [1] it was shown how a two dimensional intercept system can be viewed as a commutative bilinear system when the pursuer possesses both speed and acceleration control capabilities. Minimum energy controls were derived for a general class of such commutative bilinear systems and were shown to be particularly simple in form in that such controls are constant vectors determined by the boundary conditions. Using deterministic least squares theory for estimating the target speed and turn rate, the results in [1] were combined with a step-by-step control-estimation iterative procedure to obtain a feedback type control law in [9]. Simulation results are also included in [9] which indicate that good terminal accuracy is achieved when the estimation errors are small and illustrate the limitations on accuracy when fluctuations occur in the target speed and turn rate. Reference [8] establishes sufficient conditions for global controllability of a class of noncommutative and nonhomogenous bilinear systems using fixed point arguments and also includes some controllability results pertinent to a class of more general nonlinear systems. These results remove certain boundedness assumptions which attended previous conditions on controllability for the class of systems considered.

References [5 and 6] together with the last two topics listed in Section V pertain to a relatively new approach to system identification and parameter estimation which has been under way for the past few years under AFOSR-75-2793. This approach is characterized by the following points: (i) only input-output data on a finite time interval $0 \leq t \leq t_1$ is presumed to be given, (ii) any disturbances which may be active on $[0, t_1]$ are modeled by arbitrary solutions to a linear homogeneous differential equation of chosen order r, but with no assumptions about the initial conditions or coefficients for this equation, i.e. $2r$ degrees of freedom for any given integer r, and (iii) no attempt is made to estimate the unknown initialconditions, either in the disturbances model or the system model when parameter identification is considered. The approach is applicable to a reasonably broad class of nonlinear and time varying systems for identification purposes including the Duffing, Hammerstein, Mathieu and Van der Pol equations, and a class of bilinear systems. These examples are included in Reference [6]. The extended version of [6] includes a summary of a simulation study carried out recently for the Van der Pol equation with second order disturbances. A fourth order helicopter model with two inputs and two outputs has been used in [5] to illustrate various aspects of this identification technique including (i) computational alternatives inherent in the basic formulation, (ii) alternatives which apply to MIMO systems when partial decoupling between parameters exists within the basic model, and (iii) the sensitivity of the identification technique to modeling errors for the input and measurement noise disturbances. The simulation study carried out for this example demonstrated that parameter identification for the helicopter is feasible using input-output data over time intervals as short as one second in the presence of input and output disturbances as high as third order. This is significant in view of the fact that the helicopter possessed two real stable modes with time constants of 0.5 and 4.3 secs, plus a pair of lightly damped unstable modes, i.e. identification was feasible using a variety of inputs and initial conditions over a time interval significantly shorter than the longest stable time constant.

The basic theory presented in [6] has also been extended to include a signal estimation problem of the following type. Given a modal signal $y(t) = s(t) + v(t)$ for $0 \leq t \leq t_1$, a filter has been devised which separates the useful signal $s(t)$ from the noise $v(t)$ under the conditions: (i) the characteristic modes of $s(t)$ are known, but their amplitudes are unknown, (ii) the modes of the noise $v(t)$ as well as their individual amplitudes are arbitrary unknown quantities, although an upper bound on the number of such modes is assumed given, (iii) the signal $s(t)$ and the noise $v(t)$ do not have any modes in common on $0 \leq t \leq t_1$. These results are included in Mocenigo's M.S. thesis listed in Section VI and represent another topic among those currently in progress.

IV. REFERENCED PUBLICATIONS

[1] Wei, K. C. and Pearson, A. E., "On Minimum Energy Control of Commutative Bilinear Systems," Proc. of 1977 JACC, San Francisco. CA, pp. 839-846, June 1977. (To appear in IEEE Trans. on Auto. Contr., Vol. AC-23, No. 6, Dec. 1978)

[2] Kwon, W. H. and Pearson, A. E., "A Note on Feedback Stabilization of a Differential-Difference System," IEEE Trans. on Auto. Contr., vol. AC-22, No. 3, pp. 468-470, June, 1977.

[3] Kwon, W. H. and Pearson, A. E., "A Modified Quadratic Cost Problem and Feedback Stabilization of Linear Discrete Time Systems," Brown Univ., Div. of Engr. Tech. Rep. AFOSR-75-2793C/1, Sept. 1977.

[4] Kwon, W. H. and Pearson, A. E., "A Modified Quadratic Cost Problem and Feedback Stabilization of a Linear System," IEEE Trans. on Auto. Contr., Vol. AC-22, No. 5, pp. 838-842, Oct. 1977.

[5] Chin, Y. K. and Pearson, A. E., "Computational Aspects of Finite Time Interval Identification without State Estimation," Proc. of 1977 IEEE Conf. on Decis. and Contr., New Orleans, LA, pp. 892-897 Dec. 1977. (Submitted to IEEE Trans. on Auto. Contr.)

[6] Pearson, A. E., "Nonlinear System Identification with Limited Time Data," Preprints of IFAC VII, Vol. 3, pp. 2159-2166, Helsinki, Finland, June 1978.(Extended version to appear in Automatica, Jan. 1979.)

[7] Kwon, W.H. and Pearson, A. E., "On Feedback Stabilization of Time Varying Discrete Linear Systems," IEEE Trans. on Auto. Contr., Vol. AC-23, No. 3, pp. 479-481, June 1978.

[8] Wei, K. C. and Pearson, A. E., "Global Controllability for a Class of Bilinear Systems," IEEE Trans. on Auto. Contr., Vol. AC-23, No. 3, pp. 486-488, June 1978.

[9] Wei, K. C. and Pearson, A. E., "Control Law for an Intercept System," AIAA J. on Guid. and Contr., Vol. 1, No. 5, pp. 298-304, Sept. 1978.

V. RESEARCH IN PROGRESS

Kwon, W. H. and Pearson, A. E., "A Double Integral Quadratic Cost and Tolerance of Feedback Nonlinearities."

Pearson, A. E. and Mocengio, J. M., "A Filter for Separating Time Limited Modal Signals."

Pearson, A. E. and Mocenigo, J. M., "Adaptive Control Using a Finite Time Identification Technique."

VI. M.S. AND PH.D. THESES

Chin, Y. K., "Theoretical and Computational Considerations for Finite Time Interval System Identification Without Initial State Estimation," Ph.D. Thesis, Brown Univ., June 1977.

Mocenigo, J. M., "A Deterministic Filter from a Parameter Identification Scheme," Brown Univ., June 1978.

VII. CONSULTATIVE INTERACTIONS

(a) A visit was made to the Armament Lab at Eglin AFB, Florida, on September 7, 1978, to discuss research problems with Lt. Thomas Riggs. The control problem for a missile intercept system was discussed, particularly as it relates to the formulations given in References [1] and [9]. As a result of this consultative, plans are under way to treat a modified intercept problem in which the pursuer possesses only thrust vectoring (no thrust modulation capability).

(b) Paper Presentations, Seminars and Invited Talks.

Dec. 9, 1977: Invited paper "Computational Aspects of Finite Time Interval Identification Without State Estimation" at the 1977 IEEE Conf. on Decis. and Control, New Orleans, LA.

Jan. 26, 1978:	University of Warwick, "System Identification With Time Limited Data: Part 1 - Theory".
Jan. 31, 1978:	University of Warwick, "System Identification with Time Limited Data: Part II - Computational Considerations".
Feb. 9, 1978:	University of Warwick, "Average Power Constrained Feedback Control of Linear Systems".
Feb. 16, 1978:	University of Warwick, "Finite Time Horizon Control of Time Varying Linear Systems".
Mar. 1, 1978:	University of Manchester Institute of Science and Technology, "System Identification With Time Limited Data".
Mar. 3, 1978:	Cambridge University, "System Identification With Time Limited Data".
Mar. 8, 1978:	University of Wales Institute of Science and Technology, "System Identification With Time Limited Data".
Mar. 22, 1978:	Oxford University, "Control Law for an Intercept System With a Bilinear Interpretation".
April 7, 1978:	University of Warwick, Case Study Lecture on "Control of a Gliding Parachute System" for the Science Research Council sponsored "Spring Vacation School on Stochastic Processes, April 3rd - 7th".
April 26, 1978:	Sheffield University, "System Identification With Time Limited Data".
April 27, 1978:	Imperial College of Science and Technology, "System Identification With Time Limited Data".
May 2, 1978	University of Groningen, Holland, "System Identification With Time Limited Data".
May 3, 1978:	Twente University of Science and Technology, Holland, "System Identification With Time Limited Data".
May 10, 1978:	Catholic University of Louvain, Belgium, "System Identification With Time Limited Data".
May 10, 1978:	University Libre de Brussels, Belgium, "Control Law for an Intercept System With a Bilinear Interpretation".
May 16, 1978:	British Institution of Electrical Engineers, Colloquium on Nonlinear Systems Identification, "Least Squares Identification of Nonlinear Differential Systems With Analytical Disturbances".

May 18, 1978: (Two lectures)	University of Genoa, Italy, "System Identification With Time Limited Data" and "Control Law for an Intercept System With a Bilinear Interpretation".
May 25, 1978:	University of Warwick, "Optimal Control of a Gliding Parachute System".
June 12,16,'78	Attended the IFAC VII Congress in Helsinki, Finland and presented the paper "Nonlinear System Identification With Time Limited Data."

REPORT PREPARED BY: Allan E. Pearson

FOR GRANT: AFOSR-75-2793

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